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Harmonizing the RR Lyrae and Clump Distance Scales — Stretching the Short Distance Scale to Intermediate Ranges?

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ABSTRACT

I explore the consequences of making the RR Lyrae and clump giant distance scales consistent in the solar neighborhood, Galactic bulge and Large Magellanic Cloud (LMC). I employ two major assumptions: 1) that the absolute magnitude - metallicity, $M_V(RR) - [Fe/H]$, relation for RR Lyrae stars is universal, and 2) that absolute I -magnitudes of clump giants, $M_I(RC)$, in Baade's Window can be inferred from the local Hipparcos calibration of clump giants' magnitudes. A comparison between the solar neighborhood and Baade's Window sets $M_V(RR)$ at $[Fe/H] = -1.6$ in the range $(0.59 \pm 0.05, 0.70 \pm 0.05)$, somewhat brighter than the statistical parallax solution. A comparison between Baade's Window and the LMC sets the $M_I^{LMC}(RC)$ in the range $(-0.33 \pm 0.09, -0.53 \pm 0.09)$. The distance modulus to the LMC is $\mu^{LMC} \in (18.24 \pm 0.08, 18.44 \pm 0.07)$. I argue that the currently available information slightly favors the short distance scale but is insufficient to select the correct solutions with high confidence.

Subject Headings: distance scale — dust, extinction — Galaxy: center — Magellanic Clouds — stars: horizontal-branch — stars: variables: RR Lyrae

1. Introduction

The Hubble Space Telescope Key Project (e.g., Madore et al. 1999) concluded that the biggest uncertainty in the Hubble constant, H_0 , comes from the uncertainty in the distance to the LMC. Among the major methods that have been used to determine the distance to the LMC are: the echo of the supernova 1987A, solving parameters of eclipsing binaries, Cepheids, RR Lyrae stars, and red clump giants. They all suffer from some uncertainties and possible systematic errors. The echo of the supernova 1987A was a transient event with limited data and contradictory interpretations (Gould & Uza 1998 versus Panagia 1998). Only one attempt of solving eclipsing binary using space-based spectra was made by

Guinan et al. (1998) for HV 2274. Their result is sensitive to the reddening toward HV 2274 (Udalski et al. 1998 versus Nelson et al. 2000). To achieve a robust calibration, Cepheids have to wait for the next generation astrometric missions. The absolute V -magnitudes of RR Lyrae stars, $M_V(RR)$, are still under debate with a faint value given by the statistical parallax method and a bright value suggested by the main sequence fitting (see Popowski & Gould 1999). The major problem of the red clump method is the possibility that the absolute I -magnitude, $M_I(RC)$, is sensitive to the environment (Cole 1998; Girardi et al. 1998; Twarog, Anthony-Twarog, & Bricker 1999). The mentioned methods give results inconsistent within their estimated uncertainties, which suggests hidden systematics.

Here I concentrate on two horizontal-branch standard candles: red clump giants and RR Lyrae stars. I start with a very short review of their application to determine the distance to the LMC. Paczyński & Stanek (1998) pointed out that clump giants, should constitute an accurate distance indicator. In a study of the morphology of the red clump, Beaulieu & Sackett (1998) argued that a distance modulus of $\mu^{LMC} = 18.3$ provides the best fit to the dereddened LMC color-magnitude diagram. Udalski et al. (1998a) and Stanek, Zaritsky, & Harris (1998) applied the I -magnitude based approach of Paczyński and Stanek (1998) and found a very short distance to the LMC ($\mu^{LMC} \approx 18.1$). In response, Cole (1998) and Girardi et al. (1998) suggested that clump giants are not standard candles and that their $M_I(RC)$ depend on the metallicity and age of the population. Udalski (1998b, 1998c) countered this criticism by showing that the metallicity dependence is at a low level of about 0.1 mag/dex, and that the $M_I(RC)$ is approximately constant for cluster ages between 2 and 10 Gyr. The new determinations of the $M_I(RC) - [Fe/H]$ relation by Stanek et al. (1999), Udalski (1999) and Popowski (2000) indicate a moderate slope of 0.10 – 0.20 mag/dex. The only clump determination, which results in a truly long distance to the LMC is a study by Romaniello et al. (1999) who investigated the field around supernova SN 1987A, which is not well suited for extinction determinations. Romaniello et al. (1999) also assumed a bright $M_I(RC)$ from theoretical models. The distance modulus to the LMC from clump giants that is believed to be the least model-dependent is approximately $\mu^{LMC} = 18.24 \pm 0.08$ (Udalski 1999).

Different methods to obtain the RR Lyrae absolute magnitude are analyzed in Popowski & Gould (1999). The results depend on the methods used. When the kinematic or geometric determinations are employed, one obtains $M_V(RR) = 0.71 \pm 0.07$ at $[Fe/H] = -1.6$ (with $M_V(RR) = 0.77 \pm 0.13$ from the best understood method, statistical parallax). The other methods typically produce or are consistent with brighter values. The representative main sequence fitting to globular clusters gives $M_V(RR) = 0.45 \pm 0.12$ at $[Fe/H] = -1.6$ (Carreta et al. 1999). When coupled with Walker (1992) photometry of globular clusters, Popowski & Gould's (1999) best $M_V(RR)$ results in $\mu^{LMC} = 18.33 \pm 0.08$. When Udalski et al. (1999) –

photometry of the LMC field RR Lyrae stars is used, one obtains $\mu^{LMC} = 18.23 \pm 0.08$.

The essence of the approach presented here is a comparison between clump giants and RR Lyrae stars in different environments. If answers from two distance indicators agree then either the systematics have been reduced to negligible levels in both of them or the biases conspire to produce the same answer. This last problem can be tested with an attempt to synchronize distance scales in three different environments, because a conspiracy of systematic errors is not likely to repeat in all environments. Here I show that combining the information on RR Lyrae and red clump stars in the solar neighborhood, Galactic bulge, and LMC provides additional constraints on the local distance scale.

2. Assumptions and Observational Data

The results I present in §3 and 4 are not entirely general and have been obtained based on certain theoretical assumptions about the nature of standard candles and populations in different stellar systems. In addition, the conclusions depend on the source of photometry. One does not have much freedom in this regard, but I have made certain choices, which I describe in §2.2.

2.1. Theoretical assumptions

This investigation relies strongly on the following two assumptions:

1. The $M_V(RR) - [\text{Fe}/\text{H}]$ relation for RR Lyrae stars is universal. More specifically, I assume that for every considered system, $M_V(RR)$ is only a linear function of this system's metallicity:

$$M_V(RR) = \alpha ([\text{Fe}/\text{H}] + 1.6) + \beta. \quad (1)$$

Moreover, I will assume that the slope $\alpha = 0.18 \pm 0.03$, which is not critical for the method but determines the numerical results. In the most general case, $M_V(RR)$ depends on morphology of the horizontal branch (Lee, Demarque, & Zinn 1990; Caputo et al. 1993). However, for average non-extreme environments (here the character of environment can be judged using the Lee 1989 index) a linear, universal $M_V(RR) - [\text{Fe}/\text{H}]$ should be a reasonable description. For the RR Lyrae stars of the Galactic halo (either in the solar neighborhood or in Baade's Window) and of the LMC field or globular clusters, equation (1) with universal α and β should approximately hold. The universal character of the calibration is essential to any

distance determination with standard candles, and so this assumption is rather standard.

2. The absolute magnitude $M_I^{\text{BW}}(RC)$ of the bulge clump giants can be inferred from the Hipparcos-calibrated $M_I^{\text{HIP}}(RC)$ of the local clump stars. That is, I assume that there are no population factors except metallicity that influence $M_I^{\text{BW}}(RC)$ (with respect to the local clump) or that their contributions cancel out. Again, this is somewhat similar to point 1., but here I am more flexible allowing $M_I^{\text{LMC}}(RC)$ in the LMC not to follow the local Hipparcos calibration.

2.2. Data

The calibration of clump giants in the solar neighborhood is based on Hipparcos (Perryman 1997) data for nearly 300 clump giants as reported by Stanek & Garnavich (1998) and refined by Udalski (1999).

$$M_I^{\text{HIP}}(RC) = (-0.26 \pm 0.02) + (0.13 \pm 0.07)([\text{Fe}/\text{H}] + 0.25) \quad (2)$$

I assume that the metallicity of the bulge clump in Baade’s Window is $[\text{Fe}/\text{H}] = 0.0 \pm 0.3$ consistent with Minniti et al. (1995). As a result, I set $M_I^{\text{BW}}(RC) = -0.23 \pm 0.04$ (see eq. (2) and §2.1), where the error of 0.04 is dominated by the uncertainty in the metallicity of clump giants in Baade’s Window. The V - and I -band photometry for the bulge clump giants and RR Lyrae stars originates from, or have been calibrated to the photometric zero-points of, phase-II of the Optical Gravitational Lensing Experiment (OGLE). That is, the data for Baade’s Window come from Udalski (1998b) and were adjusted according to zero-point corrections given by Paczyński et al. (1999). When taken at face value, these data result in $(V - I)_0$ colors¹ of both clump giant and RR Lyrae stars that are 0.11 redder than for their local counterparts. To further describe the input data let me define Δ for a given stellar system as the difference between the mean dereddened I -magnitude of clump giants and the dereddened V -magnitude of RR Lyrae stars at the metallicity of RR Lyrae stars in the Galactic bulge. The quantity Δ allows one to compare the relative brightness of clump giants and RR Lyrae stars in different environments and so will be very useful for this study (for more discussion see Udalski 1998b and Popowski 2000). In the Baade’s Window with anomalous horizontal branch colors $\Delta^{\text{BW}} \equiv I_0^{\text{BW}}(RC) - V_0^{\text{BW}}(RR) = -1.04 \pm 0.04$. When the color correction considered by Popowski (2000) is taken into account one obtains $\Delta^{\text{BW}} = -0.93 \pm 0.04$.

¹Here and thereafter subscript “0” indicates dereddened or extinction-free value.

In the LMC, I use dereddened $I_0 = 17.91 \pm 0.05$ for “representative red clump”. Here “representative” means in clusters (compare to $I_0 = 17.88 \pm 0.05$ from Udalski 1998c) or in fields around clusters (compare to $I_0 = 17.94 \pm 0.05$ from Udalski 1999). The advantage of using I_0 from cluster and cluster fields is their low, well-controlled extinction (Udalski 1998c, 1999). I take $V_0 = 18.94 \pm 0.04$ for field RR Lyrae stars at $[\text{Fe}/\text{H}] = -1.6$ from Udalski et al. (1999) and adopt $V_0 = 18.98 \pm 0.03$ at $[\text{Fe}/\text{H}] = -1.9$ for the cluster RR Lyrae stars investigated by Walker (1992). The difference of photometry between Udalski et al. (1999) and Walker (1992) may have several sources. The least likely is that the cluster system is displaced with respect to the center of mass of the LMC field. Also, cluster RR Lyrae stars could be intrinsically fainter, but again this is not very probable. I conclude that the difference comes either from 1) extinction, or 2) the zero-points of photometry. The first case would probably point to overestimation of extinction by OGLE, because it is harder to determine the exact extinction in the field than it is in the clusters. The second case can be tested with independent LMC photometry. In any case, the difference of ~ 0.1 mag is an indication of how well we currently measure $V_0(RR)$ in the LMC.

Finally, let us note that the homogeneity of photometric data was absolutely essential for the investigation of the global slope in the $M_I(RC) - [\text{Fe}/\text{H}]$ relation (Popowski 2000). Here it is not as critical. Still, the common source of data for the Galactic bulge reduces the uncertainty in the $M_V(RR)$ calibration. On the other hand, the use of both OGLE and Walker’s (1992) data for the LMC quantifies a possible level of extinction/photometry uncertainty.

3. The method and results

The distance modulus to the Galactic center from RR Lyrae stars is:

$$\mu^{\text{BW}}(RR) = V_0^{\text{BW}}(RR) - M_V^{\text{BW}}(RR). \quad (3)$$

I assume the RR Lyrae metallicities of $[\text{Fe}/\text{H}]_{RR}^{\text{BW}} = -1.0$ from Walker & Terndrup (1991). The distance modulus to the Galactic center from the red clump can be expressed as:

$$\mu^{\text{BW}}(RC) = I_0^{\text{BW}}(RC) - M_I^{\text{BW}}(RC). \quad (4)$$

The condition that $\mu^{\text{BW}}(RR)$ and $\mu^{\text{BW}}(RC)$ are equal to each other² results in:

$$M_I^{\text{BW}}(RC) - M_V^{\text{BW}}(RR) = I_0^{\text{BW}}(RC) - V_0^{\text{BW}}(RR) \quad (5)$$

²For this condition to be exactly true one has to take into account the distribution of clump giants in the bar and RR Lyrae stars in the spheroidal system as well as completeness characteristics of a survey. The analyses from OGLE did not reach this level of detail, but I neglect this small correction here.

But the right hand side of equation (5) is just Δ^{BW} , which is either directly taken from dereddened data or determined by solving the color problem (for more detail see Popowski 2000). If there are no population differences between the clump in Baade’s Window and the solar neighborhood (as we assumed in §2.1), then $M_I^{BW}(RC)$ is extremely well constrained from the Hipparcos results reported in equation (2). Therefore, equation (5) is in effect the calibration of the absolute magnitude of RR Lyrae stars:

$$M_V^{BW}(RR) = M_I^{BW}(RC) + \Delta^{BW} \quad (6)$$

If one calibrates the $M_V(RR) - [\text{Fe}/\text{H}]$ relations according to equation (6), then by construction the solar neighborhood’s and the Baade’s Window’s distance scales are consistent.

To determine $M_I^{LMC}(RC)$, I construct the Udalski’s (1998b) diagram. However, both Udalski (1998b) and Popowski (2000) used such diagrams to determine a global slope of the $M_I(RC) - [\text{Fe}/\text{H}]$ relation. Because I am interested here just in the LMC, a more powerful approach is to treat the Udalski (1998b) diagram in a discrete way. That is, instead of fitting a line to a few points one takes a difference between the Baade’s Window and LMC Δ as a measure of the $M_I(RC)$ differences in these two stellar systems. Therefore:

$$M_I^{LMC}(RC) = M_I^{BW}(RC) - (\Delta^{BW} - \Delta^{LMC}) \quad (7)$$

The interesting feature of equation (7) is that the calibration of $M_I^{LMC}(RC)$, even though based on RR Lyrae stars, is independent of the zero-point β of the $M_V(RR) - [\text{Fe}/\text{H}]$ relation. Because $M_I^{LMC}(RC)$ leads to a specific value of μ^{LMC} , coupling μ^{LMC} with the LMC RR Lyrae photometry allows one to calibrate the zero-point of the $M_V(RR) - [\text{Fe}/\text{H}]$ relation. However this calibration is not independent of the one presented in equation (6) and so does not provide any additional information.

Using equations (6) and (7), I calibrate the zero point of $M_V(RR) - [\text{Fe}/\text{H}]$ relation as well as $M_I(RC)$ of clump giants in the LMC. The solutions are listed in Table 1. Different assumptions about the color anomaly in the Galactic bulge and the use of either OGLE-II or Walker’s (1992) photometry in the LMC result in four classes of $[M_V(RR), M_I^{LMC}(RC)]$ solutions (column 1). Following argument from §2.2, I use one universal I_0 for clump giants in the LMC (column 2). The brighter RR Lyrae photometry in the LMC comes from OGLE (Udalski et al. 1999) and the fainter from Walker (1992) [column 3]. In column 4, I report Δ^{LMC} , which has been inferred from columns 2 and 3 assuming the the slope α in the $M_V(RR) - [\text{Fe}/\text{H}]$ relation is 0.18. In column 5, I give Δ^{BW} . The resulting $M_V(RR)$ at $[\text{Fe}/\text{H}] = -1.6$, $M_I^{LMC}(RC)$, and the LMC distance modulus are shown in columns 6, 7, and 8, respectively.

4. Discussion

Using RR Lyrae stars and clump giants, I showed that the requirement of consistency between standard candles in different environments is a powerful tool in calibrating absolute magnitudes. If the anomalous character of $(V - I)_0$ in Baade’s Window is real (i.e., not caused by problems with photometry or misestimate of the coefficient of selective extinction), then the distance scale tends to be shorter. In particular, $M_V(RR) = 0.70 \pm 0.05$ at $[\text{Fe}/\text{H}] = -1.6$, and the distance modulus to the LMC spans the range from $\mu^{LMC} = 18.24 \pm 0.08$ to 18.33 ± 0.07 . If $(V - I)_0$ color of stars in Baade’s Window is in error and should be standard, then the distance scale is longer. In particular, one can obtain $M_V(RR) = 0.59 \pm 0.05$ at $[\text{Fe}/\text{H}] = -1.6$ and the distance modulus from $\mu^{LMC} = 18.35 \pm 0.08$ to 18.44 ± 0.07 . Are there any additional constraints that would allow one to select the preferred value for RR Lyrae zero point β , $M_I^{LMC}(RC)$, and μ^{LMC} ? The fact that indirectly favors the intermediate distance scale is its consistency with the results from classical Cepheids. The value of $M_V(RR)$ required for such solution is only 1.4σ (combined) below the “kinematic” value of Popowski & Gould (1999) and 1.3σ (combined) below the statistical parallax result given by Gould & Popowski (1998), leaving us without a decisive hint. The Twarog et al. (1999) study of two open Galactic clusters (NGC 2420 and NGC 2506) indicates rather bright red clumps. However, the relevance of this result to the LMC is uncertain and, more importantly, its precision is too low to provide significant information. The Beaulieu and Sackett (1998) study of clump morphology in the LMC suggests $\mu^{LMC} \sim 18.3$, probably consistent with the entire (18.24, 18.44) range. The only significant clue is provided by Udalski’s (1999) spectroscopically-based investigation of the red clump in the solar neighborhood. If uncorrelated metallicity and age are the only population effects influencing $M_I(RC)$ in different environments, then Udalski (1999) results coupled with theoretical modeling lend strong support to the shorter distance scale. However, unless the selective extinction coefficient toward Baade’s Window is unusual, very short distance scale comes at a price of anomalous $(V - I)_0$ bulge colors. Therefore, one is tempted to ask: “Is it normal that $M_I(RC)$ follows the local prescription and $(V - I)_0$ does not?”. In summary, with currently available photometry, it is possible to obtain the consistent RR Lyrae and clump giant distance scales, which differ by as much as 0.2 magnitudes. It is clear that further investigations of population dependence of $M_I(RC)$, the Galactic bulge colors and the zero points of the LMC photometry are needed to better constrain the local distance scale.

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TABLE 1
VARIOUS SOLUTIONS FOR $M_V(RR)$, $M_I^{\text{LMC}}(RC)$ AND μ^{LMC} .

Solution	$I_0^{\text{LMC}}(RC)$	$V_0^{\text{LMC}}(RR)$	Δ^{LMC}	Δ^{BW}	$M_V(RR)^a$	$M_I^{\text{LMC}}(RC)$	μ^{LMC}
anomalous + OGLE	18.91 ± 0.05	18.94 ± 0.04^a	-1.14 ± 0.07	-1.04 ± 0.04	0.70 ± 0.05	-0.33 ± 0.09	18.24 ± 0.08
anomalous + Walker	18.91 ± 0.05	18.98 ± 0.03^b	-1.23 ± 0.07	-1.04 ± 0.04	0.70 ± 0.05	-0.42 ± 0.09	18.33 ± 0.07
standard + OGLE	18.91 ± 0.05	18.94 ± 0.04^a	-1.14 ± 0.07	-0.93 ± 0.04	0.59 ± 0.05	-0.44 ± 0.09	18.35 ± 0.08
standard + Walker	18.91 ± 0.05	18.98 ± 0.03^b	-1.23 ± 0.07	-0.93 ± 0.04	0.59 ± 0.05	-0.53 ± 0.09	18.44 ± 0.07

^a at $[\text{Fe}/\text{H}] = -1.6$

^b at $[\text{Fe}/\text{H}] = -1.9$

NOTE.—The solutions are classified according to $(V - I)_0$ colors in the Galactic bulge (uncorrected – *anomalous* or corrected – *standard*), and the source of LMC RR Lyrae photometry: Udalski et al. (1999) – *OGLE* or Walker (1992). The errors in Δ^{LMC} , $M_V(RR)$, and $M_I^{\text{LMC}}(RC)$ include the uncertainty in the slope of the $M_V(RR) - [\text{Fe}/\text{H}]$ relation as well as 0.1 dex uncertainty of metallicity difference between different stellar systems. Careful inspection of the definition of Δ , distance modulus, and equation (7) shows that $M_I^{\text{LMC}}(RC)$ depends on $I_0^{\text{LMC}}(RC)$, whereas μ^{LMC} does not. As a result, the error in μ^{LMC} is smaller.